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This investigation evaluated the feasibility of developing a fast and efficient computational tool for optimized design of advanced, slow-wave, traveling-wave-tube-amplifiers (TWTAs). Because of their high power, broad-bandwidth, compact size, and high efficiency features, TWTAs are relied upon for satellite communications; airborne, shipborne, and ground-based radar; jamming and decoy applications. Because it is crucial to keep the time between conceptualization and finished product to an absolute minimum, the most effective design tools need to quickly assess new concept feasibility and generate initial design guidelines.

The investigators successfully obtained 1D frequency dependant impedances and phase velocities from a 3D electromagnetic analysis of helix waveguides and incorporated them into a 1D, fully time-domain dispersive TWTA model. A "proof-of-concept" has been verified, including a demonstration of reasonable accuracy by comparing the new algorithm's predictions with a linear regime, 1D, analytic model. Advances have also been made in the development of a 3D time-dependent TWT interaction model for benchmarking purposes.

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Computational Tools for Optimized Design of Advanced Traveling Wave Tubes
Contract number F4920-99-C-0064-DEF (STTR Phase I)

I Key Personnel

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II Project Objectives

The objective of this research was to demonstrate the feasibility of developing efficient computational tools for optimized design of advanced traveling wave tube amplifiers. Traveling wave tube amplifiers (TWTAs) are slow-wave, vacuum-electron, microwave sources that command a ubiquitous strategic presence in the communications and electronic warfare missions of all Armed Services, as well as in commercial market sectors. Because of their high power, broad-bandwidth, compact size, and high efficiency features, TWTAs are relied upon for satellite communications; airborne, shipborne, and ground-based radar; jamming and decoy applications. Commercial applications include satellite communications, radar, and materials processing. Recent technological breakthroughs have made it possible to fabricate TWTAs with ultra-large instantaneous bandwidth (approaching three octaves, in some cases). New applications are therefore being imagined, based in part, on this new ultra-large bandwidth capability, as well as new digital signal processing ideas for advanced, secure, high-data-rate communications. However, many of these applications assume highly linear TWTA performance, including during multi-toned operation (i.e., when driven by multiple, simultaneous, carrier signals or "tones"). In fact, many of the emerging interests for TWTAs demand high linearity over a very broad bandwidth while maintaining high efficiency. This is one of the greatest challenges—and opportunities—ever faced by TWTA designers, due to the inherently nonlinear electron-beam-wave interaction. An illustration of a linearity challenge is seen in Figure 1, where a broadband (6-18 GHz) TWTA, driven by four carrier signals on the input, yields not only the four amplified drive "tones" but a dense spectra of satellite signals, including harmonics, intermodulation products (IMPs) and higher-order products of the harmonics and IMPs.

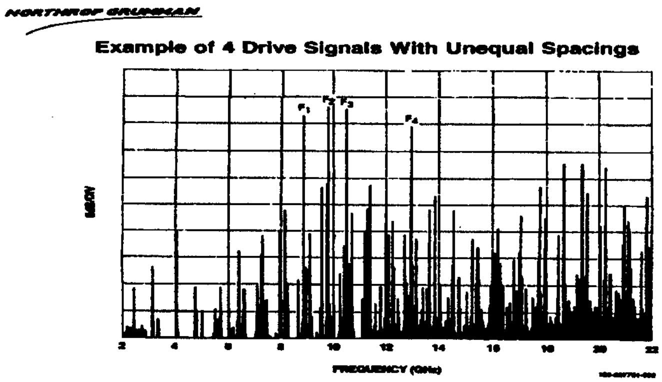

Figure 1 Dense intermodulation and harmonic output spectra for a 4-tone excitation of a 6-18 GHz broadband TWTA

Multiple strategies are available for linearization, including external equalization, internal circuit modification, and beam optics optimization. Cost-effective design and production considerations indicate that maximizing the linearity-efficiency performance product via circuit design, helps to lessen the need for costly, solid-state, pre-distortion circuits for signal equalization. However, in addition to linearity and efficiency, there are always other performance specifications to be met, including minimum gain, minimum bandwidth, maximum device length, robust stability from backward wave oscillations, etc. Simultaneous attention to all of these objectives and requirements is a daunting, iterative, and potentially expensive process.

There are several alternative philosophies on the wisest approach to realize a successful TWTA design that best satisfies the many ambitious constraints posed by advanced applications. Perhaps the most traditional method is to “cut metal”: i.e., run through a series of prototype experimental devices, guided by experience and intuition on each successive design modification. Modern TWTA designers, however, are resorting to a greater usage of computer design tools in advance of cutting metal. In principle, such simulation tools can save a considerable amount of resources from being wasted on designs that have non-obvious, but critical flaws. However, one of the most important concerns in modern markets (both Defense and commercial) is time; it is crucial to keep the time between conceptualization and finished product demonstration to an absolute minimum. *Hence, the most effective computer design tools will include those that can quickly assess the feasibility of new concepts and generate critical initial design guidelines.* More exact (e.g., computationally slower, 2.5 and 3D) computer models, should and do play an important role in validating and refining these initial designs. However, the additional computational time and resources they require make them poorly suited to rapid, first-cut “optimization” or synthesis-type calculations. Because of the dense, complex spectra that can arise with highly-multitoned operation (for example, see Figure 1), the code should be a fully-time-domain model, rather than a frequency-domain, "normal mode", or "slowly-varying envelope" code.

Thus, the objective of this Phase I effort was to develop an efficient computational tool for optimized, initial-stage design of advanced TWTAs. To serve as an early-stage

guide in the design process (rather than just benchmark and confirm), the model must be fast, yet capable of exploring many different design parameters available to the TWTA engineer. This argues for a 1D code. A long-range objective of the research will be to develop an efficient, 1D optimization code with realistic representation of physical 3D circuit features. Phase I research was restricted to showing feasibility of key features of the 1D TWTA design model.

III Work Performed

The following tasks were achieved to complete the Phase I objectives:

Task 1 – Extraction of 1D TL-equivalent impedance functions from 3D electromagnetic analyses of helix waveguides.

In this task, 3D electromagnetic computer calculations were performed using MAFIA (Solution of **MA**xwell's equations by the **F**inite-**I**ntegration-**A**lgorithm) [i, ii] on a single turn helix with dielectric support rods and metallic vanes using quasi-periodic axial boundary conditions. Cold-test data and mode diagrams were produced for several geometric variations to the circuit. The code's proven computational abilities were used to obtain frequency-dependent, series inductance-per-unit-length, shunt capacitance-per-unit-length, and series turn-to-turn capacitance for a representative helix/support-rod/metallic vane circuit. The intent was that these functions will share similar fabrication constraints that are faced by the TWTA fabrication engineer and will therefore be realistically reversible to realize physical circuit solutions equivalent to the prescribed, optimal impedance functions.

Task 2 – Construction of an efficient, 1D, time-domain (PIC), dispersive TWTA code.

For feasibility evaluation, the feasibility to formulate a fully-time-domain TWTA PIC model that includes the dispersive TL properties of a physical helix, as revealed and generated from Task 1 was examined. Recent advances in numerical absorbing boundary conditions were investigated, but not fully incorporated into this first version. The model was evaluated for accuracy, computational speed, and relative ease in specification of the dispersive circuit functions.

Task 3 – Incorporate turn-to-turn series capacitance into the time-domain, TL, TWTA model.

A thorough model should predict the existence of spatial harmonics and BWO phenomena owing to backwards-propagating circuit wave modes. The intended technical approach was to realize this physics by adopting turn-to-turn series capacitance within the model. In fact, the primary objective of realizing 2D or 3D geometric dispersion effects within a 1D, lossless, time-domain model proved extremely challenging. As a result, this Task 3 embellishment became outside the scope of work achievable within the Phase I time and resource limitations. Nevertheless, discussions with Dr. Richard Carter of Lancaster University (UK) indicated that the expected outcome of this objective was well-founded, and may, indeed, succeed if pursued in a subsequent research investigation. Dr. Carter has established expertise in the modeling of helix transmission lines using lumped circuit models.

Task 4 – Benchmark results of 1D code against established codes.

Several predictive characteristics of the prototype 1D code were compared with results from established or more exact codes. In addition, the prototype 1D design code was evaluated for computational speed and efficiency and ease of use. Based on these performance evaluations, the potential utility of this tool as a practical TWTA design aid, especially if coupled to an adaptive optimizer algorithm, was assessed.

IV Results Obtained

The purpose of this study was to develop a fast simulation tool, which could be used in the preliminary design of traveling wave tubes. Specification goals for that tool included that it be: (1) One-dimensional, (2) Time-domain and producing (3) Realistic dispersion. The tool consists of two main parts, a modified telegrapher's equation to model the wave on the helix and a particle–in-cell (PIC) code to model the electron beam. These are then coupled together using Ramo's theorem [iii] to impress the beam-induced image current on the helix and using the spatial derivative of the helix voltage to determine the electric field, which modifies electron motion in the beam.

IV.1 Modified Telegrapher's Equation

The main innovation of this work is the development of a technique for including 2D and 3D waveguide dispersion effects in a 1D, time-domain code. To accomplish this, the telegrapher's equations were modified. The telegrapher's equations are a pair of coupled differential equations which describe RF current and voltage on a transmission line using distributed capacitance and inductance.

$$\begin{aligned} \frac{\partial V}{\partial t} &= -\frac{1}{C}\frac{\partial I}{\partial z} \\ \frac{\partial I}{\partial t} &= -\frac{1}{L}\frac{\partial V}{\partial z} \end{aligned} \tag{1}$$

The equations are derived from an analysis of the equivalent circuit model for a lossless, dispersionless, transmission line (shown in Figure 2).

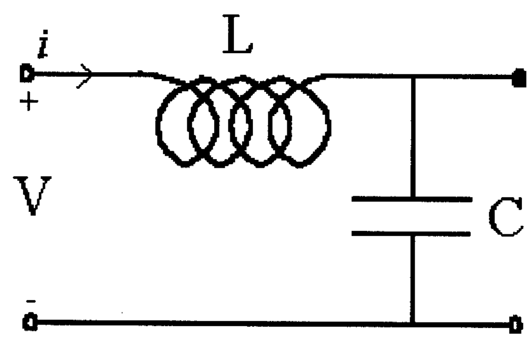

Figure 2 **Unit cell for circuit model of conventional, lossless, dispersionless transmission line.**

The phase velocity and characteristic impedance of the wave traveling on this line are

$$v_p = \frac{1}{\sqrt{LC}} \tag{2}$$

$$K = \sqrt{\frac{L}{C}} \tag{3}$$

As is apparent from these equations, this model is dispersionless. All frequencies propagate with the same velocity.

The telegrapher's equations, although 1D, can be used to simulate 2D and 3D systems in a limited fashion. If the phase velocity and one component of both the electric and magnetic field are known at a specific frequency, the telegrapher's equations can model the system at that frequency. Dispersion can only be introduced into these equations if resistance R and conductance G are added to the distributed unit cell or if the inductance L and capacitance C are made to be frequency-dependent. These solutions have undesirable side effects. The use of R and G creates artificial loss in the system and the use of frequency-dependent L and C requires solving the equations in the frequency domain at each time step.

The approach adopted in this investigation was to modify the conventional LC network. By adding extra inductors and capacitors one can introduce dispersion on the line while still using constant (frequency independent) L's and C's. Different combinations of L's and C's will yield different dispersion relations. The distributed circuit chosen as a proof-of-principle experiment is shown in Figure 3.

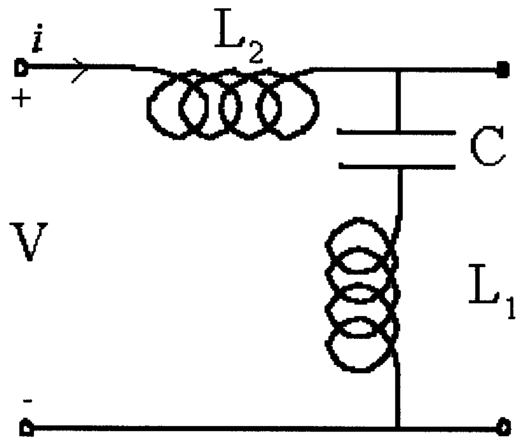

Figure 3 Unit cell for circuit model of lossless, dispersive 1D transmission line.

A simple analysis of this modified circuit yields the following modified telegrapher's equations:

$$\frac{\partial V}{\partial t} = -\frac{1}{C}\frac{\partial I}{\partial z} - L_1 \frac{\partial^2}{\partial t^2}\frac{\partial I}{\partial z}$$
$$\frac{\partial I}{\partial t} = -\frac{1}{L_2}\frac{\partial V}{\partial z} \tag{4}$$

The dispersion relation associated with these equations is similar in form to the dispersion relation of an illustrative, realistic helix TWT circuit as determined from the 3D-modeling tool MAFIA. As shown in Figure 4, proper choice of L1, L2, and C yields , a 1-D dispersion relation which approximates the 3D dispersion relation.

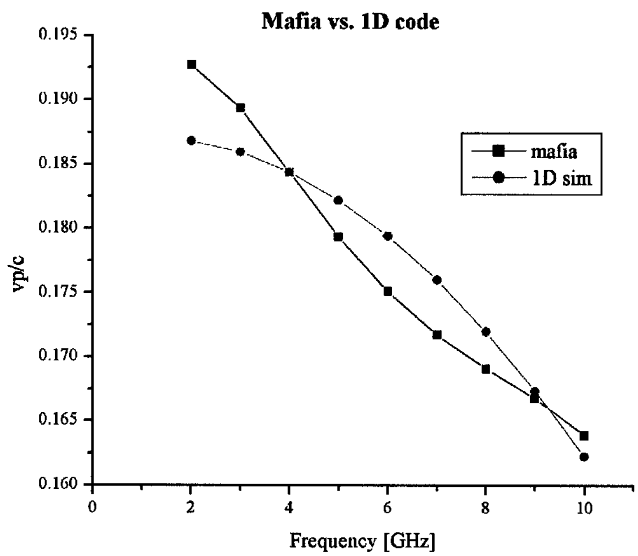

Figure 4 Comparison of modified telegrapher's equation and realistic TWT dispersion.

The coupled partial differential equations (4) were numerically solved using a finite difference time-domain (FDTD) algorithm. Central finite differencing resulted in an implicit scheme for advancing the voltage and current on the transmission line.

Validation of the preliminary code was accomplished by launching a broadband Gaussian pulse down the transmission line and recording the signal as a function of time at two observation points. A Fourier transform of the two recorded signals yielded a phase difference between the two points in space, which is the propagation constant β. From this data, the phase velocity was calculated as a function of frequency f as

$$v_p = \frac{\omega}{\beta} = \frac{2\pi f}{\beta}. \tag{5}$$

FDTD-computed phase velocity showed excellent agreement, over the entire bandwidth of the pulse, with the phase velocity as is shown in Figure 5.

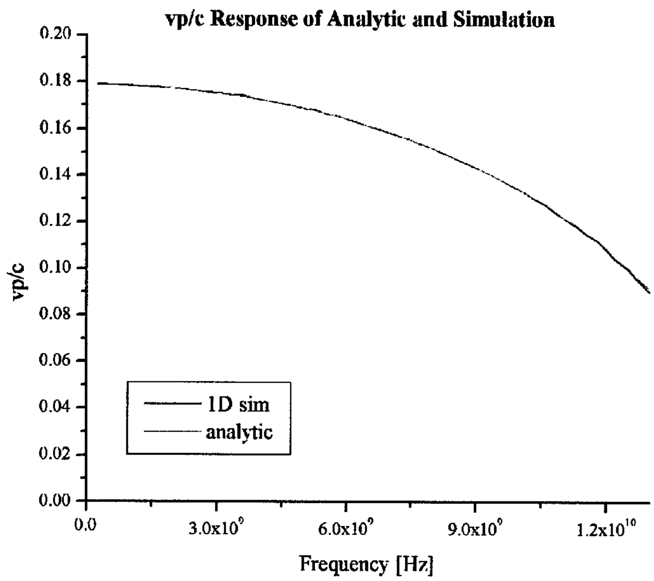

Figure 5 Comparison of simulated and analytically determined dispersion.

IV.2 PIC Code

The next major component of the model is the PIC code. Macro particles, which represent a number of electrons, and which have the same charge to mass ratio as an electron, are launched from the gun and propagated along the axis using the leapfrog method to determine velocity and position, v and x, respectively, as

$$v_{new} = v_{old} + a_{ave}\Delta t$$
$$x_{new} = x_{old} + v_{ave}\Delta t \qquad (6)$$

where v and x are the velocity and position, respectively, a is the acceleration, and v and x are offset in time by $\Delta t/2$. This is the scheme used in Birdsall's IBC code [iv].

From the positions and velocities of the macro particles, a current is mapped to the grid. This current is then added to the coupled differential equations (4) to model the effect of the electron beam on the helix voltage.

The effect of the line voltage on the electrons (in the beam) is calculated from the electric field determined from the gradient of the line voltage.

$$E = -\frac{\partial V}{\partial z} \qquad (7)$$

The PIC code and the cold circuit portion of the model combine to produce the desired simulation tool.

To validate the combined model, it was compared to the analytically determined response of a TWT in the linear regime. The voltage along the TWT for the analytic model is determined from the equation below

$$V(z,t) = \sum_{i=1}^{3} \int_{-\infty}^{\infty} F_i(\omega) e^{j(\omega t - y_i(\omega) z)} e^{x_i(\omega) z} d\omega \tag{8}$$

where $F_i(\omega)$ is the input signal in the frequency domain, $x_i(\omega)$ and $y_i(\omega)$ are the imaginary and real parts of the three forward-propagating roots of the determinental equation which describes the response of the 1D TWT, respectively. Only the three roots that represent the forward propagating waves are used, as the backward traveling wave is not excited in the simulation.

A case for a differentiated Gaussian input signal is shown in Figure 6. The analytic and simulation models are compared in the linear regime (i.e., well before saturation) in Figure 7.

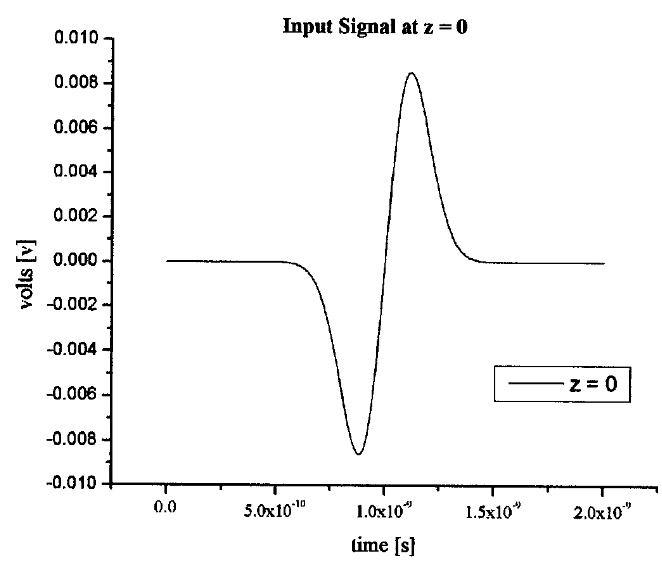

Figure 6 Input signal into TWT at z = 0.

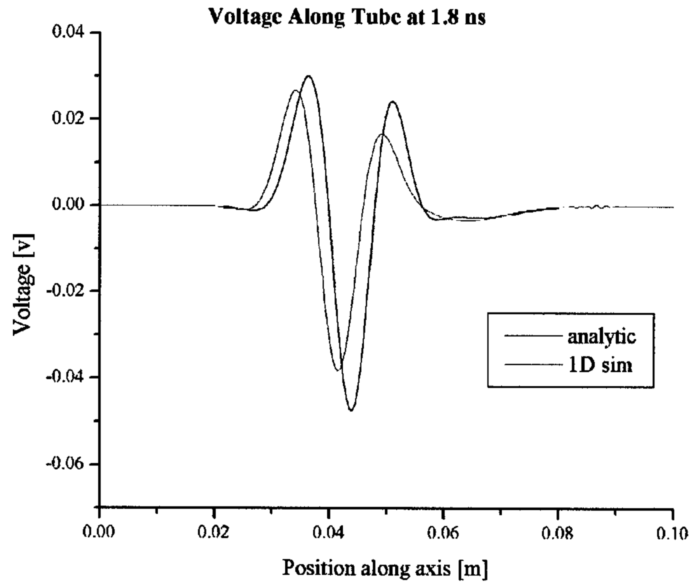

Figure 7 Comparison of simulated and analytically determined response of TWT at t = 1.8 ns.

The 1D numerical simulation is in close agreement with the exact analytical model, including both dispersion and frequency-dependent gain. Remaining disagreement is believed to be related to the algorithm chosen for modeling the beam-induced image currents on the helix. Alternative, superior algorithm choices have been identified, but their incorporation into the model was not possible within the Phase I period of the grant. Nevertheless, Phase I work has successfully met the objective of demonstrating the feasibility of a 1D numerical TWT time-domain model that simulates realistic dispersion effects.

In order to validate the 1D model, efforts toward completing a fully 3D, time-dependent, helical TWT interaction model using MAFIA were also undertaken. The model includes a short section of helical slow-wave circuit with excitation fed by RF input/output couplers, and electron beam contained by periodic permanent magnet (PPM) focusing. A cutaway view of several turns of the 3D helical slow-wave circuit with input/output couplers is shown in Figure 8. It has been shown that this pioneering model is more accurate than conventionally used 2D models [v].

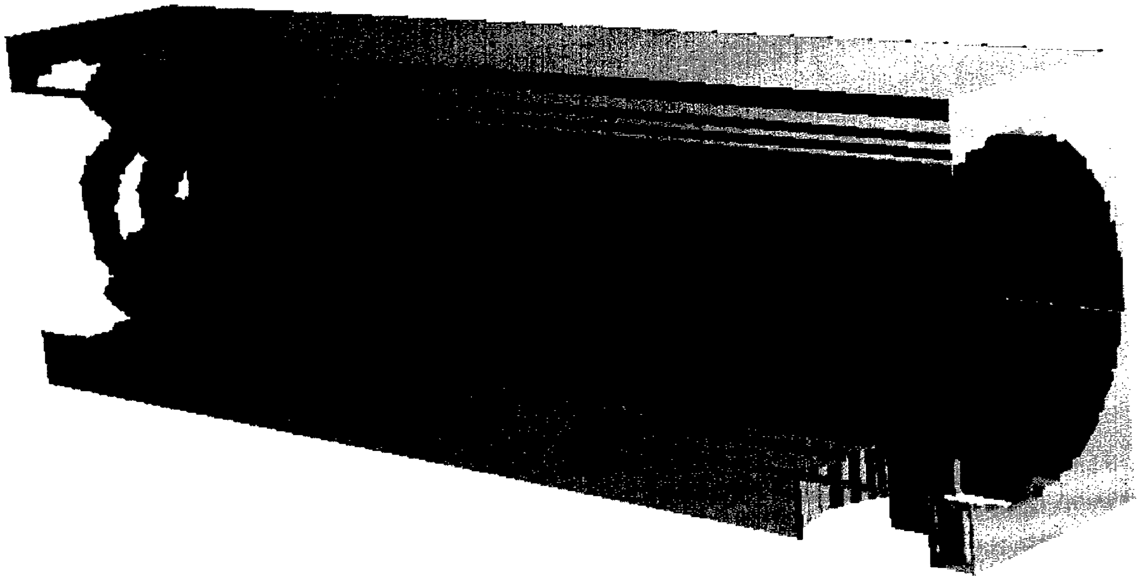

Figure 8 Cutaway of several turns of the helical slow-wave circuit with input/output couplers

V Estimate of Technical Feasibility

The overall objective was to develop a fast and physically accurate TWTA optimal-design tool. Phase I objectives were to evaluate feasibility of key elements of the larger objective. The specific objectives of the Phase I program can be enumerated as follows:

1. Establish the feasibility of extracting frequency-dependent 1D transmission-line-equivalent distributed impedances from 3D electromagnetic analyses of helix waveguides.
2. Establish the feasibility of developing a 1D, fully-time-domain (finite difference, particle-in-cell) TWTA model that includes dispersion.
3. Establish the feasibility of incorporating the results of objective 1 into objective 2, so that the model dispersion is physically realistic.
4. Establish the feasibility of incorporating absorbing boundary conditions that eliminate numerical reflections.
5. Establish the feasibility of incorporating frequency-dependent turn-to-turn series capacitance into the time-domain TL TWTA model. Evaluate the hypothesis that this should introduce spatial harmonics and BWO phenomena in a physically realistic manner.
6. Confirm the basic accuracy of the tool via benchmarking calculations.

The investigators successfully obtained 1D frequency dependant impedances and phase velocities from a 3D electromagnetic analysis of helix waveguides and incorporated them into a 1D, fully time-domain dispersive TWTA model. This 1D time-domain, fully-dispersive model appears to be a true innovation and is being evaluated for

Intellectual Property claim possibilities. Subsequent publications will also be forthcoming on this significant achievement.

Because of the greater-than-expected challenge of incorporating multi-dimensional geometric dispersion into the 1D fully time-domain numerical algorithm, absorbing boundary conditions were investigated only briefly. Important insights were gained on incorporating advanced absorbing boundary conditions into the model. Nevertheless, full incorporation of a working absorbing boundary condition eventually fell outside the scope of achievable objectives within the resources and 12 months of the Phase I investigation. Also, the incorporation of a turn-to-turn series capacitance was eventually determined to be outside the scope of realistically accomplishable goals given the available resources and time constraints. However, the absence of this capacitance does not seem to affect the accuracy of the model for forward propagating waves.

The investigators have verified the "proof-of-concept", including a demonstration of reasonable accuracy, by comparing our new algorithm's predictions with a linear regime, 1D, analytic model. Advances have been made in the development of a 3D time-dependent interaction model for benchmarking purposes.

VI Facilities/Equipment

The investigators have extensive modern facilities, which were used to complete the described research.

VI.1 University of Wisconsin

UW facilities include both computational and experimental laboratories. We have ten high performance UNIX workstations for computer simulations, storing and analyzing experimental data. This includes three state-of-the art multiprocessor Sun ultra SPARC workstations. Eight of the workstations are connected via a dedicated high speed fiber optic network (FDDI).

The UW investigators have access to, and/or experience with related state-of-the-art microwave vacuum electronic software resources, including EGUN (2.5D electron trajectory code), MAGIC-2D, and-3D (2&3D PIC codes), ANSOFT-MAXWELL-2D & -3D (EM statics solvers), ANSOFT-HFSS (3D RF fields solver), HPHFSS (3D RF fields solver), OOPIC (2.5D PIC code), IBC (1D TWT PIC code), CHRISTINE (1D slowly-varying-envelope code), TRACE-3D (3D beam envelope code), TOSCA and POISSON (magnetic design codes).

For the purpose of experimental evaluation of the computational tool, Prof. Booske directs a well-equipped microwave vacuum electronics laboratory. This laboratory facility specifically has three Hewlett Packard microwave signal synthesizers and a swept-frequency (BWO) source, 3 wideband, 1 Watt solid state amplifiers, a 10 kHz-to-20 GHz spectrum analyzer, two high speed digitizing oscilloscopes (2 GS/sec), and 2-18 GHz broadband hetero- (or homo-) dyne detection circuit. We have several commercial TWTA test vehicles to use for experimental benchmarking of the TWTA design code. Furthermore, we are currently discussing with several microwave tube companies the possibilities of acquiring another laboratory test vehicle specifically designed to provide experimental benchmarking of the planned computer code.

VI.2 Analex Corporation

The Analex Corporation is a contractor for the Glenn Research Center (GRC), Cleveland, Ohio, providing TWT computational modeling and design support for the Electron Device Technology Branch of the Communications Technology Division. Facilities include two high performance UNIX workstations including a state-of-the art multiprocessor Sun ultra SPARC workstation. The group has two licenses (enabling six simultaneous simulations) for the 3D electro-dynamics code, MAFIA (Solution of **MA**xwell's equations by the **F**inite-**I**ntegration-**A**lgorithm). This code is used by Carol Kory to obtain accurate helical TWT results. It should be noted that this helical circuit modeling is a unique capability and cannot be completed elsewhere.

VII Publications

The following publications and presentations summarize, in part, the results achieved during the described STTR Phase I project period.

1. M. C. Converse, M. M. McNeely, J. H. Booske, J. E. Scharer, C. L Kory, and D. Zavadil, Investigations of nonlinearities and multi-tone response in a broad band, high gain, helix traveling wave tube amplifier, *IEEE International Vacuum Electronics Conference (IVEC),* May 2-4, 2000 in Monterey, California.

2. M. M. McNeely, M. C. Converse, J. H. Booske, J. E. Scharer, C. L Kory and D. Zavadil, Nonlinear Characterization and comparison with simulation of a high gain, broad band helix traveling wave tube amplifier, *IEEE International Conference on Plasma Science (ICOPS)* June 4-7, 2000 in New Orleans, Louisiana.

3. M. C. Converse, J. H. Booske, Y. Y. Lau, S. C. Hagness, M. M. McNeely, M. A. Wirth, J. E. Scharer and C. Wilsen, Investigation of Transients and Pulses in Traveling Wave Tubes, 42nd Annual Meeting of the APS Division of Plasma Physics combined with the 10th International Congress on Plasma Physics, Quebec City, Canada, October 23 – 27, 2000.

4. C. L. Kory , Investigation of Three-Dimensional Helical RF Field Effects on TWT Beam/Circuit Interaction, submitted to *IEEE Trans. on Electron Devices*

5. C. L. Kory, Fully Three-Dimensional Helical TWT Beam/Circuit Interaction Model, *NASA Glenn Research Center at Lewis Field Research and Technology2000,* Technical Memorandum, 2000.

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iv I. Moray and C Birdsall: Traveling-Wave-Tube Simulation: The IBC Code, IEEE Trans. Plas. Sci., vol. 18, pp. 482 – 489, 1990.
v C. L. Kory: Three-dimensional simulations of PPM Focused Helical Traveling-wave tubes, Doctor of Engineering Dissertation, Cleveland State University, Cleveland, Ohio, May 2000.